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(54) **LOW-PROFILE, VERY WIDE BANDWIDTH AIRCRAFT COMMUNICATIONS ANTENNAS USING ADVANCED GROUND-PLANE TECHNIQUES**

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(22) Filed: **Jun. 28, 2012**

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(51) **Int. Cl.**

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H01Q 3/44	(2006.01)
H01Q 21/06	(2006.01)
H01Q 9/28	(2006.01)

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CPC ***H01Q 3/446*** (2013.01); ***H01Q 1/286*** (2013.01); ***H01Q 9/285*** (2013.01); ***H01Q 21/062*** (2013.01); ***H01Q 21/26*** (2013.01)

(58) **Field of Classification Search**
CPC ... H01Q 3/446; H01Q 21/062; H01Q 5/0086; H01Q 1/48; H01Q 9/065; H01Q 1/286–1/287
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See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,313,716	B1	11/2001	Apostolos
6,323,814	B1	11/2001	Apostolos
6,359,599	B2	3/2002	Apostolos
6,373,440	B2	4/2002	Apostolos
6,373,446	B2	4/2002	Apostolos
6,384,792	B2	5/2002	Apostolos
6,404,391	B1	6/2002	Apostolos
6,480,158	B2	11/2002	Apostolos
6,486,850	B2	11/2002	Apostolos
6,492,953	B2	12/2002	Apostolos
6,504,508	B2	1/2003	Apostolos
6,590,543	B1	7/2003	Apostolos

(Continued)

OTHER PUBLICATIONS

Jay, Frank (Ed.), IEEE Standard Dictionary of Electrical and Electronics Terms, Second Edition, The Institute of Electrical and Electronics Engineers, Inc., New York, NY, 1977, p. 636.

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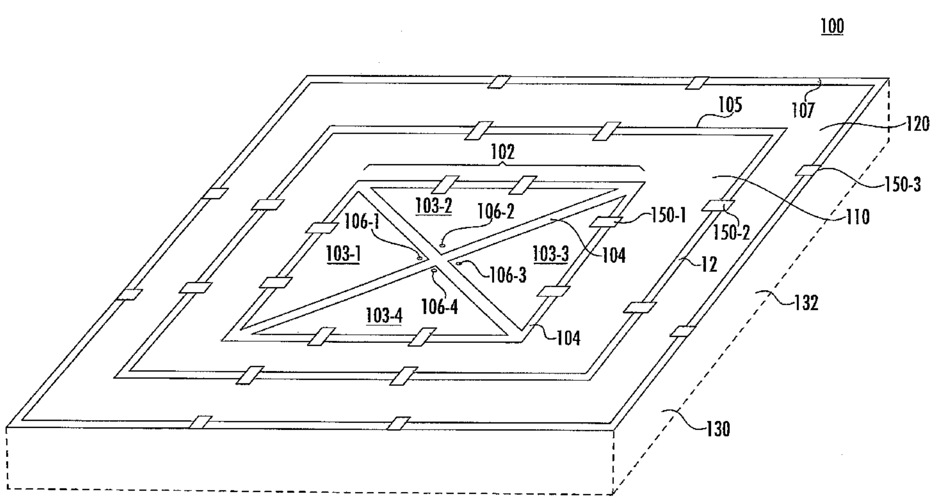
(57) **ABSTRACT**

A low profile antenna using a cavity-backed central radiating surface surrounded by one or more ground plane surfaces. Passively reconfigurable structure provide frequency dependent coupling between the surfaces. The frequency dependent couplings may be implemented using meander line structures, Variable Impedance Transmission Lines (VITLs), or tunable VITLs that used interspersed electroactive sections.

10 Claims, 10 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

6,597,321	B2 *	7/2003	Thursby et al.	343/744
6,731,247	B2	5/2004	Apostolos	
6,753,816	B1	6/2004	Apostolos	
6,771,224	B2	8/2004	Apostolos	
6,774,745	B2 *	8/2004	Apostolos	333/161
6,791,502	B2	9/2004	Apostolos et al.	
6,828,947	B2 *	12/2004	Apostolos et al.	343/895
6,833,815	B2	12/2004	Apostolos	
6,839,036	B1	1/2005	Apostolos et al.	
6,842,154	B1	1/2005	Apostolos	
6,856,288	B2	2/2005	Apostolos et al.	
6,882,322	B1	4/2005	Apostolos et al.	
6,894,656	B2	5/2005	Apostolos et al.	
6,900,770	B2	5/2005	Apostolos	
6,903,689	B2	6/2005	Apostolos et al.	
7,109,927	B2	9/2006	Gilbert et al.	
7,167,137	B2	1/2007	Apostolos	
7,190,322	B2	3/2007	Apostolos et al.	
7,209,092	B2	4/2007	Apostolos et al.	
7,358,920	B2	4/2008	Apostolos et al.	
7,436,369	B2 *	10/2008	Apostolos	343/741
7,586,453	B2	9/2009	Apostolos	
7,589,684	B2	9/2009	Apostolos	
7,609,215	B2	10/2009	Apostolos	
7,623,075	B2 *	11/2009	Apostolos	343/700 MS
8,081,130	B2	12/2011	Apostolos et al.	
8,816,925	B2	8/2014	Apostolos et al.	

* cited by examiner

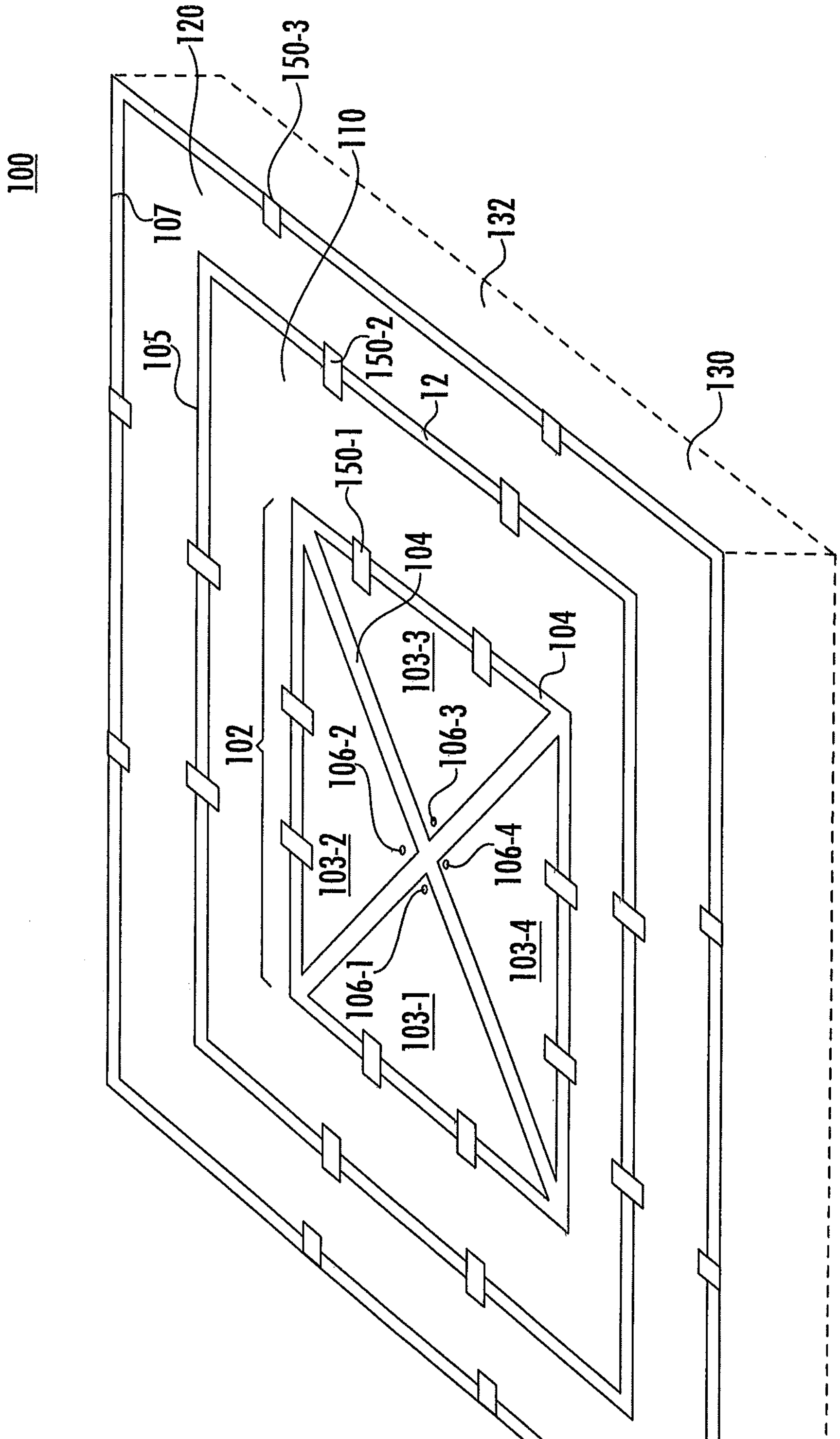

100
120
150-3
110
107
132
105
150-2
12
130
150-1
104
104
103-3
102
106-2
106-3
106-4
103-2
103-4
106-1
103-1

FIG. 1

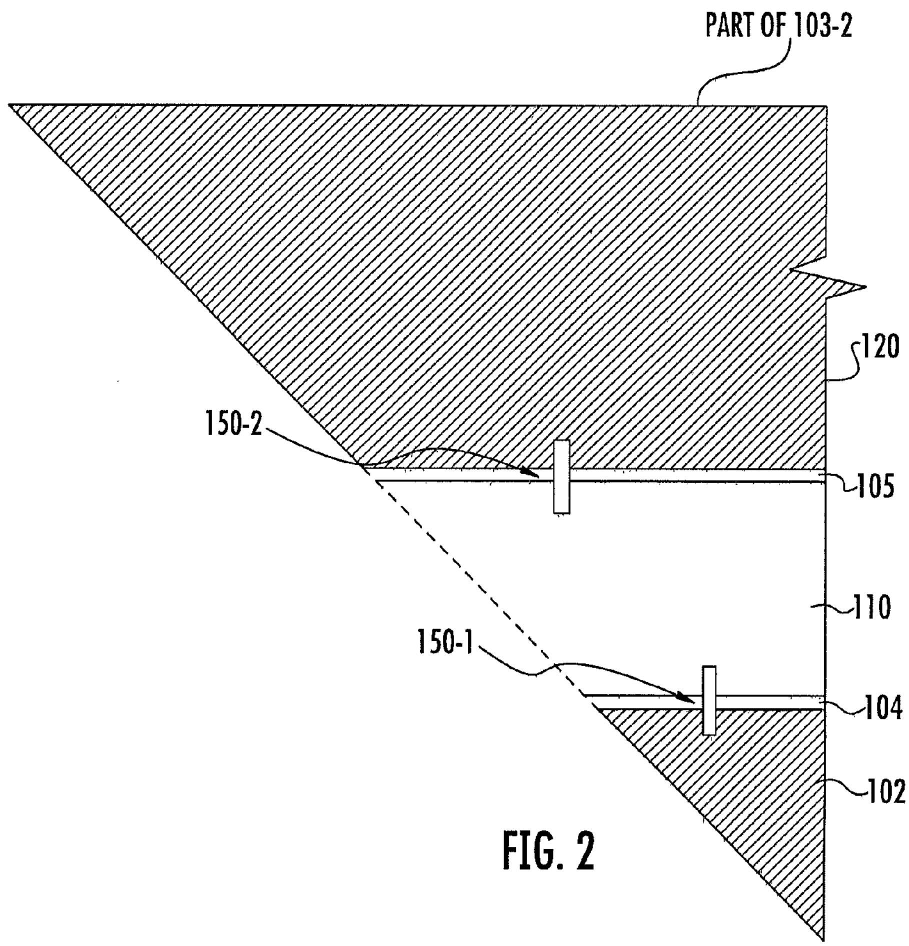


FIG. 2

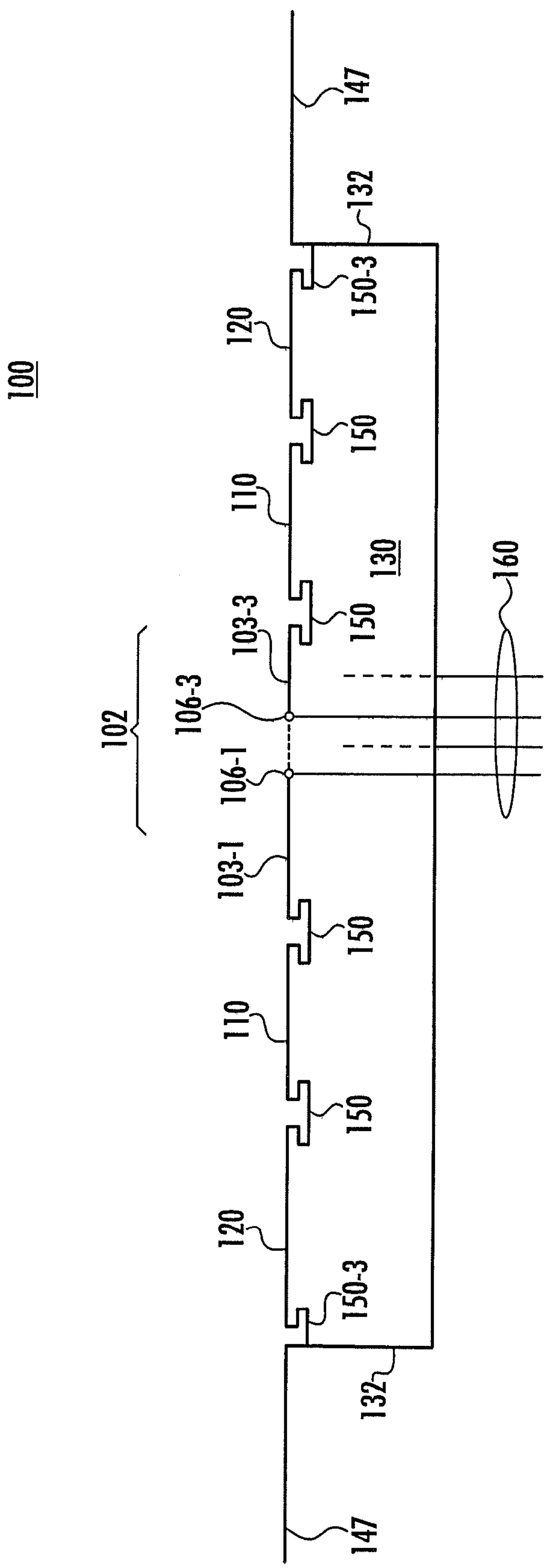

100
147
132
150-3
120
150
110
130
150
103-3
160
102
106-3
106-1
103-1
150
110
150
120
150-3
132
147

FIG. 3

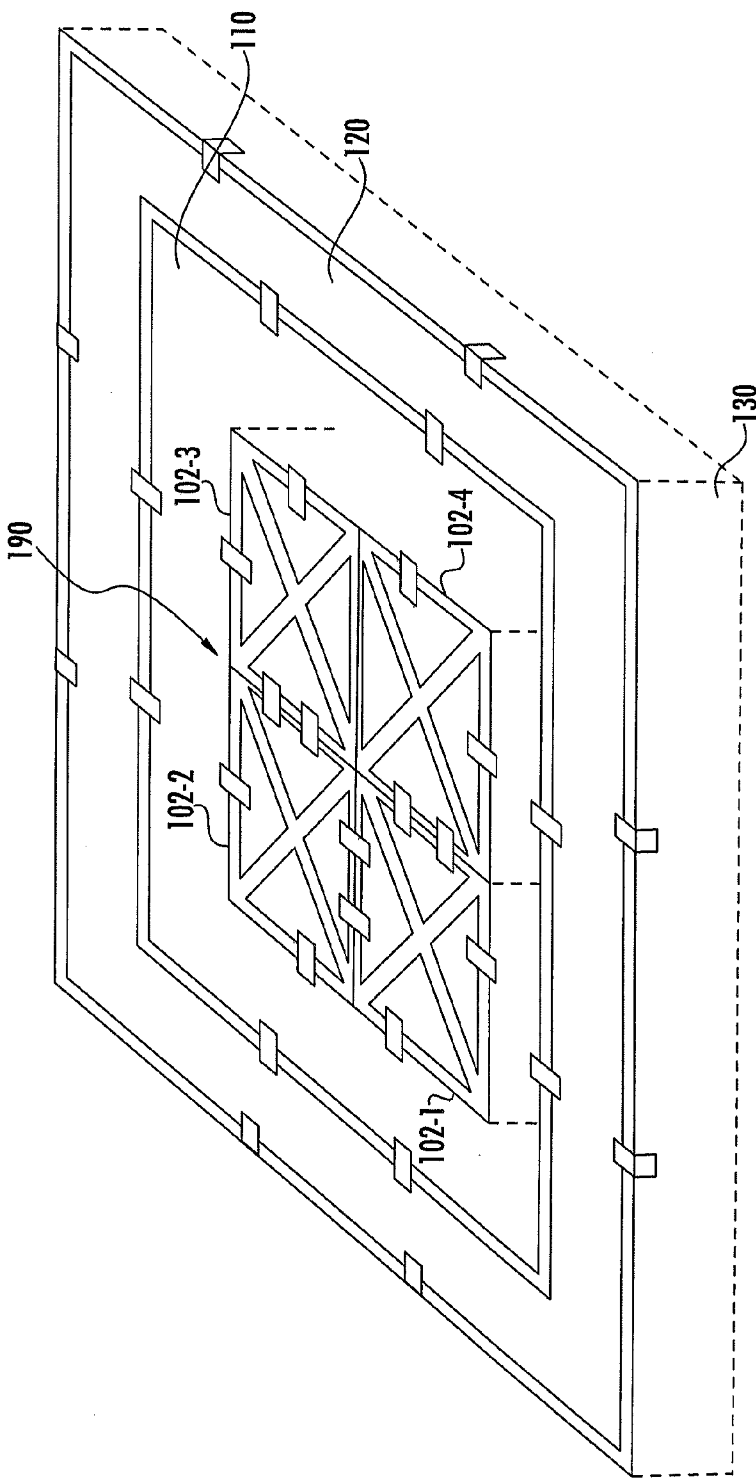


FIG. 4

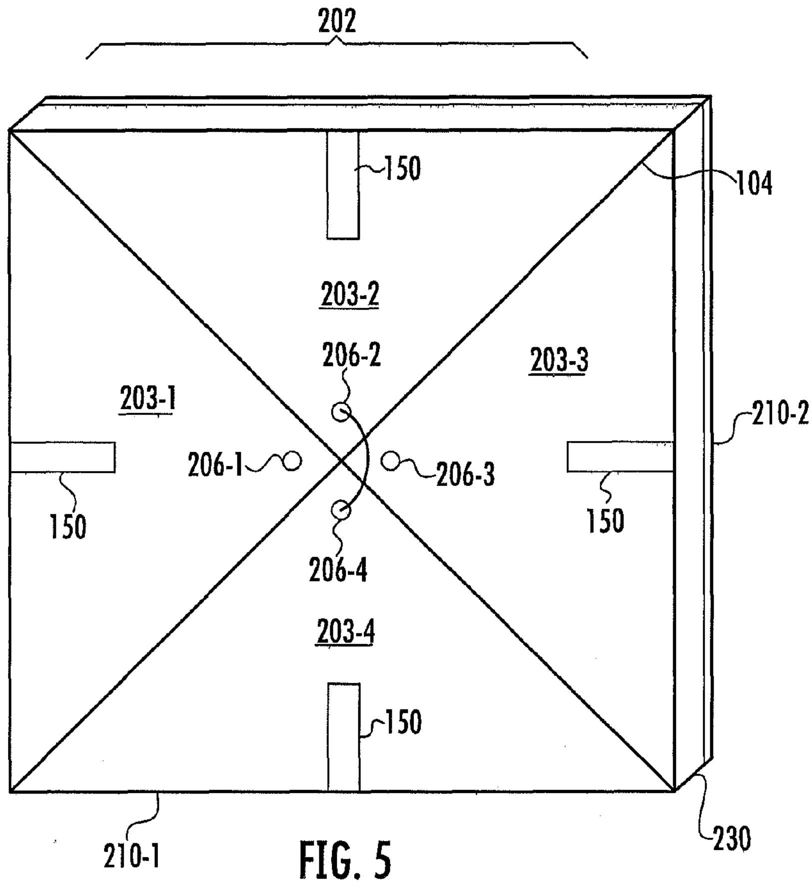

202
150
104
203-2
206-2
203-3
203-1
210-2
206-1
206-3
150
150
206-4
203-4
150
210-1
230

FIG. 5

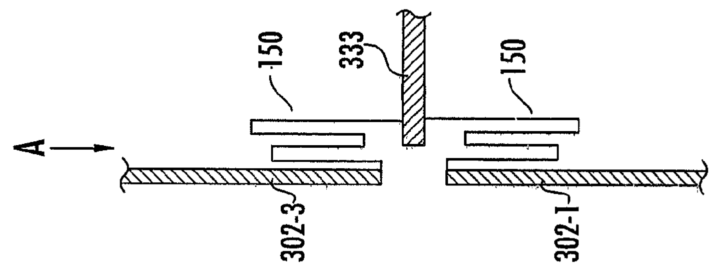


FIG. 6C

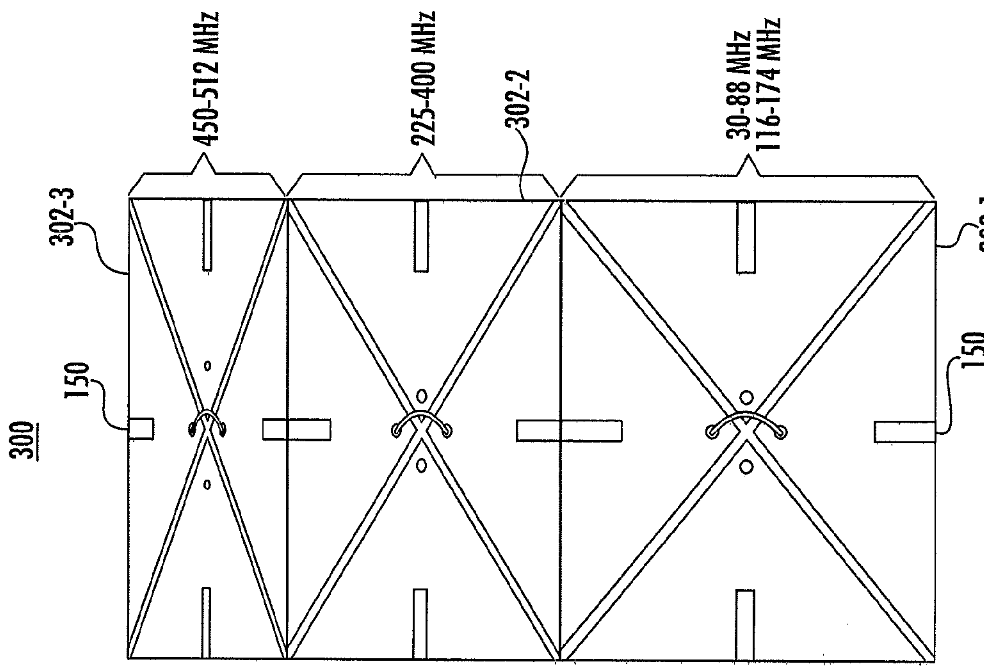


FIG. 6B

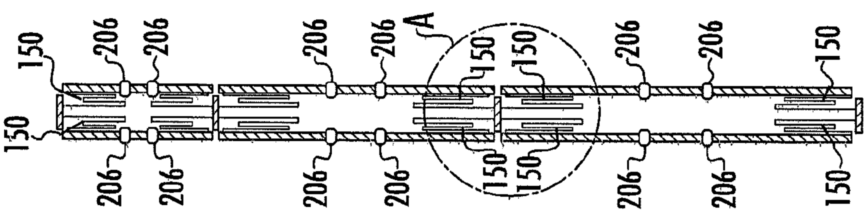


FIG. 6A

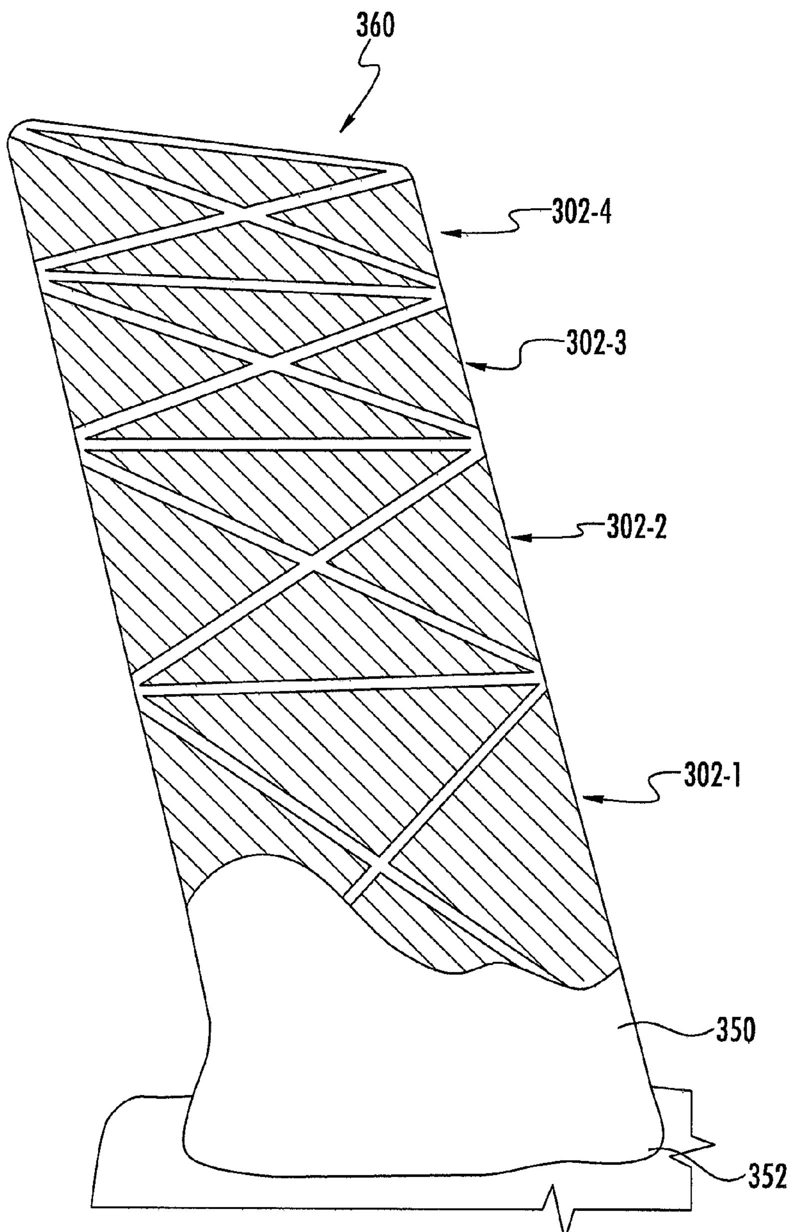


FIG. 7

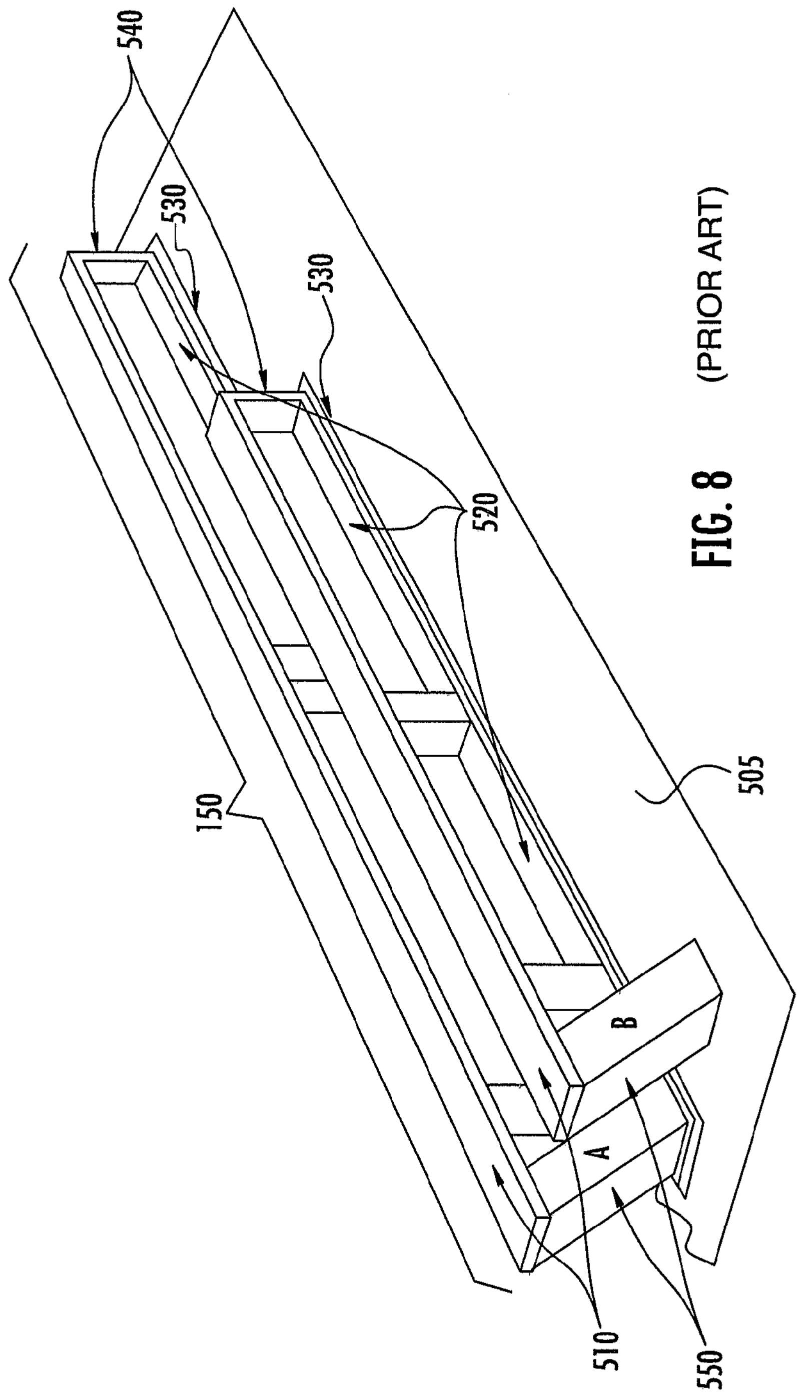


FIG. 8 (PRIOR ART)

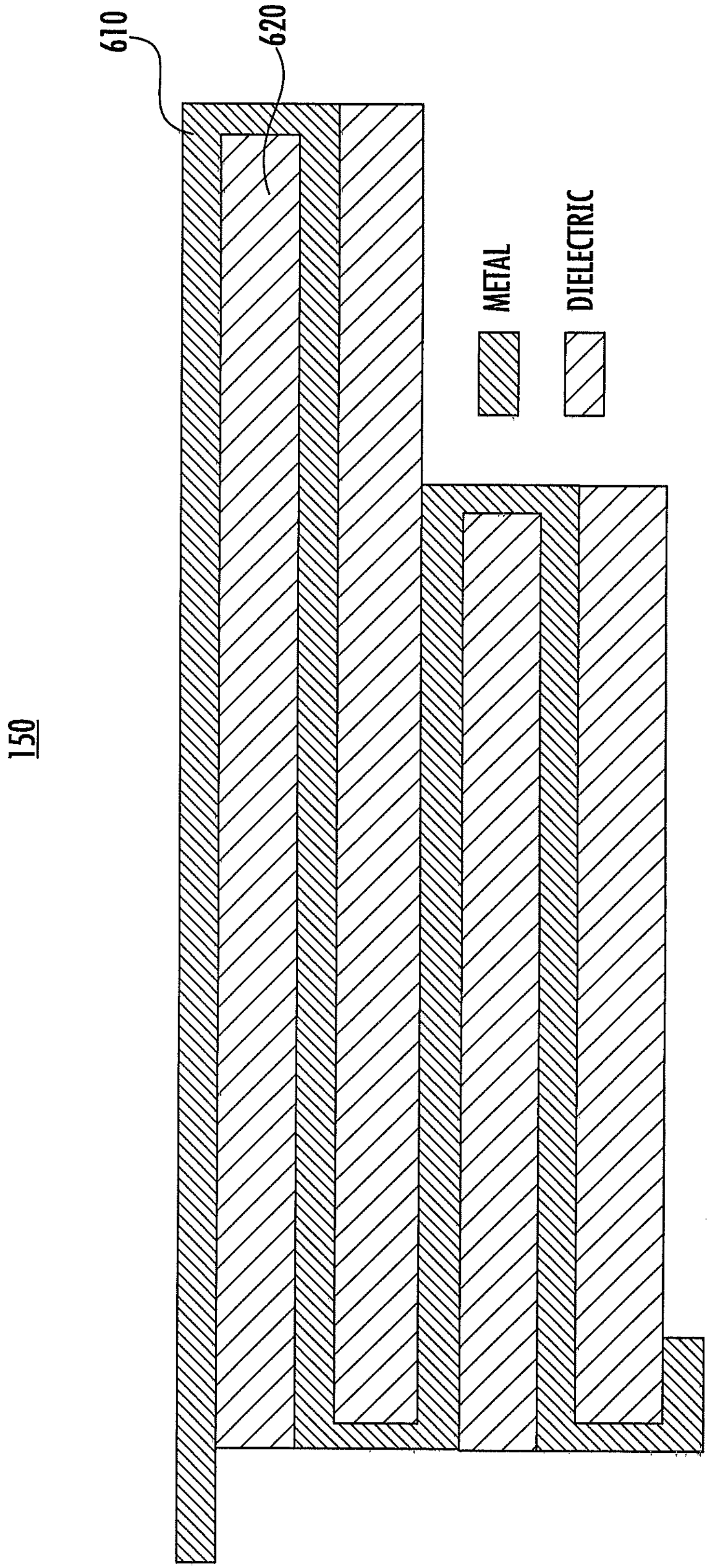


FIG. 9

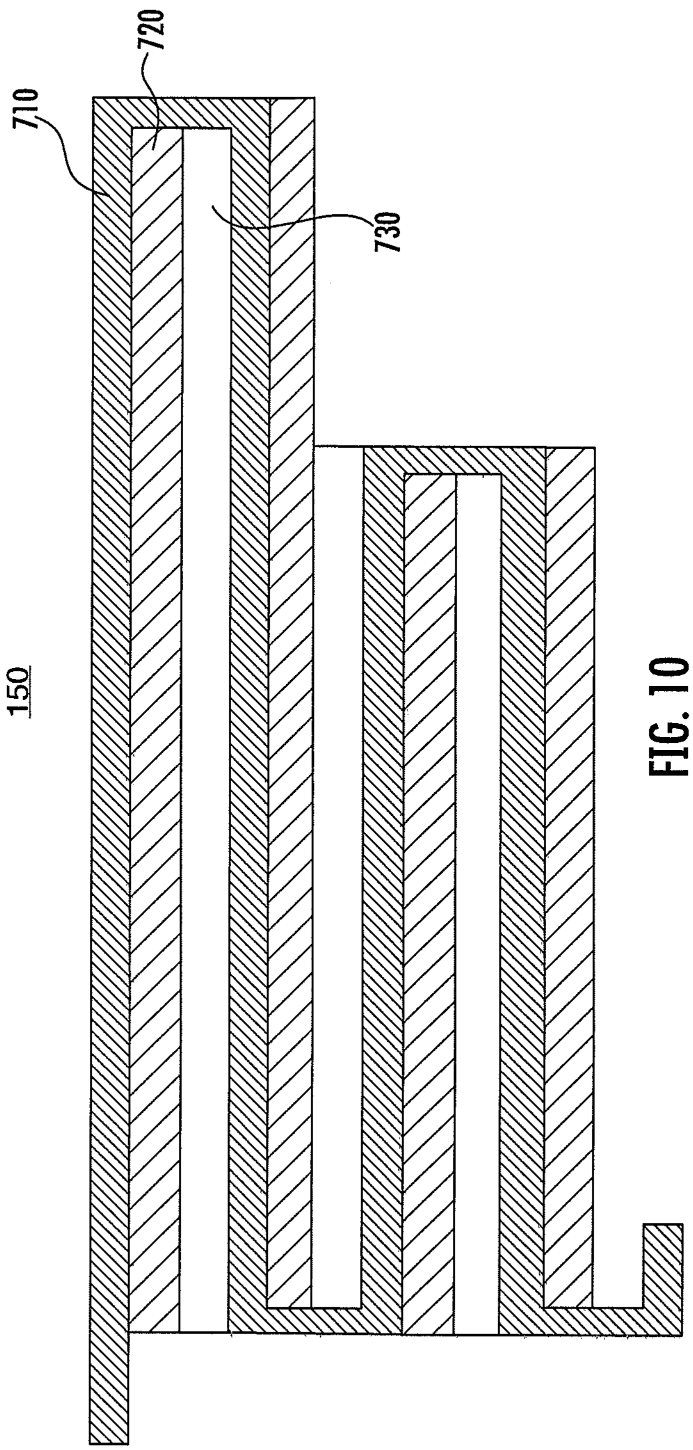


FIG. 10

LOW-PROFILE, VERY WIDE BANDWIDTH AIRCRAFT COMMUNICATIONS ANTENNAS USING ADVANCED GROUND-PLANE TECHNIQUES

RELATED APPLICATION(S)

This application claims the benefit of U.S. Provisional Application No. 61/502,246, filed on Jun. 28, 2011, U.S. Provisional Application No. 61/582,887 filed on Jan. 4, 2012; U.S. Provisional Application No. 61,590,894 filed on Jan. 26, 2012 and U.S. Provisional Application No. 61/596,972 filed on Feb. 9, 2012.

The entire teachings of the above application(s) are incorporated herein by reference.

BACKGROUND

This application relates to low profile, conformal antennas.

It is known that wide bandwidth, miniaturized antennas can be provided using planar conductors fed through frequency-dependent impedance elements such as meander lines. By arranging these components in an appropriate configuration, the electrical properties of the antenna can be passively and automatically optimized over a wide bandwidth. In one arrangement, a conductive surface placed over a conductive cavity serves as a primary radiator, and meander line components are embedded within the conductive cavity. This approach is particularly useful in aircraft and other vehicle applications since no part of the antenna needs to protrude beyond the skin of the vehicle. The approach can also be adapted to wireless devices and laptop computers and the like where the antenna height can be minimized.

In one specific implementation, a wideband antenna can be provided using these techniques that covers not only the cellular telephone frequencies, but also the Personal Communicator System (PCS), IEEE 802.11 (Wi-Fi) and GPS frequency bands. See for example U.S. Pat. No. 7,436,369 issued to Apostolos.

SUMMARY

According to various teachings herein, a low profile antenna is provided by a cavity-backed central radiating surface. The central radiator is further surrounded by one or more additional conductive surfaces that act as ground plane elements. Passively reconfigurable surface impedances operate as a frequency dependent coupling between the central radiator and the ground plane elements(s). The surrounding ground plane elements are further connected to cavity walls with the passively reconfigurable couplings.

The center radiating element is designed to operate efficiently, decoupled from the ground plane elements, at a relatively high radiation frequency of interest. The ground plane elements, being coupled to the central radiator in a frequency-dependent fashion, only become active as the frequency decreases. As the radiating frequency decreases, the active ground plane gradually expands to eventually the entire top surface of the structure when the lowest design frequency is reached.

The frequency dependent couplings may be implemented using meander line structures. The meander line structures may take various forms such as interconnected, alternating, high and low impedance sections disposed over a conductive surface.

The frequency dependent couplings may also take the form of a Variable Impedance Transmission Line (VITL) that consists of a meandering metallic transmission line with gradually decreasing section lengths, with interspersed dielectric portions to isolate the conductive segments. Specific embodiments of the VITL structure may further include electroactive actuators that alter the spacing between dielectric and metal layers to provide a Tunable Variable Impedance Transmission Line (TVITL).

In other embodiments, the canonical center radiating element may take the form of a generally rectangular (or other quadrilateral) radiating structure with four facing triangular conductive sections. The triangular sections are electrically connected into two crossed, bow-tie structures to provide circular polarization. With this arrangement of conductive surfaces, coverage can be provided in a hemispherical radiation pattern from the horizon to the zenith (or nadir, depending on installation orientation) using a planar, conformal structure.

In still other arrangements, an array of center radiating cells can be placed in a common plane. The entire array is then surrounded with one or more ground plane sections. In this arrangement the array of radiating cells can approach the operation of a monopole antenna with a conformal planar surface.

In one particular implementation, the center radiating cell may be duplicated on both sides of a common cavity. This arrangement thus consists of four triangular elements disposed back to back, providing two outward radiating surfaces. These elements may then stacked in a vertical array to provide even broader bandwidth coverage than is possible with a single cell. The multiple stacked elements are coupled to one another through additional variable impedance couplings such as meander lines, VITL, or TVITLs.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing will be apparent from the following more particular description of example embodiments of the invention, as illustrated in the accompanying drawings in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating embodiments of the present invention.

FIG. **1** is a perspective view of a low-profile cavity-backed antenna.

FIG. **2** is a more detailed top view of the antenna of FIG. **1**.

FIG. **3** is a cross-sectional view of the antenna of FIG. **1**.

FIG. **4** illustrates an array of unit cells that can provide a monopole-like response.

FIG. **5** is an implementation with a unit cell disposed on both sides of a rectangular cavity.

FIGS. **6**A, **6**B, and **6**C are a cross section, front view, and detailed view of a vertically stacked array.

FIG. **7** is a vertically stacked array arranged as a blade type antenna.

FIG. **8** is one possible implementation of a variable coupling structure.

FIG. **9** is another implementation of the variable coupling structure.

FIG. **10** is a still further implementation of a variable coupling structure.

DETAILED DESCRIPTION

A description of example embodiments follows.

The teachings of all patents, published applications and references cited herein are incorporated by reference in their entirety.

This document describes various low-profile, conformal antenna solutions that incorporate ground plane, element array, and electroactive materials in novel ways. The approaches discussed here are particularly useful in aircraft and other vehicle communication uses. However, they can also be used to provide antennas wherever low profile is important, such as in portable wireless communication devices. In general, the solutions presented here combine conformal and/or low-profile antenna technology with passive tuning technology to yield a reconfigurable surface impedance structure that can cover a wide range of frequencies.

The general approach is to provide a cavity-backed surface radiator as a center radiating element with one or more surrounding ground plane structure(s). The ground plane(s) and center radiator are connected to one another using passive, frequency dependent, coupling circuits. These couplers provide the desired turning to achieve high power capability (100 Watts) and low Voltage Standing Wave Ratio (VSWR) within the low-profile form factor.

Turning attention to FIG. **1**, a first implementation of one such conformal antenna structure **100** is shown. The antenna structure **100** consists of a center radiating surface **102** (also called a cell herein) surrounded by one or more controlled impedance ground plane surfaces **110**, **120**. An innermost, or first, ground plane cell **110** is positioned closest to an electrically surrounds the center radiating cell **102**. The outermost or second ground plane cell **120** is adjacent to and electrically surrounds the first ground plane cell **110**. While the ground plane cells **110**, **120** are shown to each consist of a single, unitary, uniform, unbroken, conductive surface that completely surround the center cell, it should be understood that these cells may be made of individual pieces spaced closely enough to one another to appear as a single surrounding surface at the operating frequencies of interest.

The center radiator **102** and ground plane cells **110**, **120** are positioned over a cavity **130** that is defined by conductive walls **132**.

Passive frequency dependent tuning structures, herein called couplers **150**, are disposed between the center cell **102** and first ground plane cell **110**, and between the first ground plane cell **110** and second ground plane cell **120**, and between the second ground plane cell **120** and walls **132** of cavity **130**.

The resulting antenna pattern is hemispherical when the center element is circularly polarized. Circular polarization can be achieved by implementing the center element as a pair of crossed bow-tie radiators. As shown, these include four, generally triangular shaped, radiating surfaces **103-1**, **103-2**, **103-3**, **103-4** arranged within the confines of the generally rectangular center radiator **102**. The triangular radiating surfaces are arranged with their respective bases along a corresponding side of the rectangle, and their peaks adjacent one another. Each triangular section **103** has a respective feed point **106** that is electrically combined with the feed points from the other sections **103** such as by using hybrid combiners. The resulting radiation pattern extends in a hemispherical pattern from the horizon to zenith (or nadir, depending on the orientation installation).

Two of the elements **103-1**, **103-3** thus form a first bowtie and the two other elements **103-2**, **103-4** form the other bowtie.

Each of the center radiator cell **102** and ground plane cells **110**, **120** are generally defined by conductive surfaces with a dielectric or other non-conductive spacing in between each cell **102**, **110**, **120**. For example, spaces **104** are provided between the various conductive surfaces of center radiator **102** and between center radiator **102** and the innermost ground plane cell **110**, and space **105** similarly is provided between the first ground plane cell **110** and the second ground plane cell **120**.

Various types of coupling structures **150** can be used, preferred implementations of which are described in greater detail below. What is important is that the couplers **150** provide frequency dependent, passive change in impedance.

The coupling structures **150** disposed between the center cell **102** and ground plane cells **110**, **120** either prevent coupling, provide partial coupling, or allow coupling of electromagnetic energy between the cells **102**, **110**, **120** depending upon the frequency band of operation. Currents generated in each of the respective ground planes from the central radiator coupling are therefore significant and greater than that of a passive ground plane depending on operating frequency. More particularly, only the center cell **102** is active at the highest operating frequency, with the couplings isolating both of the ground plane cells **110**, **120**. However as the radiating frequency decreases, the inner ground plane cell **110** becomes active, and as the frequency increases further, the outer ground plane cell **120** becomes active. As the operating frequency reaches the lowest designed frequency, both ground plane cells **110**, **120** become active and the radiating surface eventually expands to include the entire surface of the antenna structure **100**.

The size of the cavity **130** dictates the gain of the overall structure **100**. For example, based on the Chu-Harrington relationship, for a minimum frequency of operation of 30 MHz, the cavity **130** should scale to a form factor of approximately 64"×64"×2" in depth. With these dimensions, the antenna structure **100** and is expected to provide a gain of −7 dBi (decibels isotropic).

FIG. **2** is a top view of one half of one of the triangular elements **103-2**. It is presented to show in more detail a portion of center radiator **102**, ground planes **110**, **120**, and respective spaces **104**, **105** between the center element **102** and first ground plane **110** and between the first **110** and second ground plane **120**. Also shown is the relative orientation of the coupling structures **150-1**, **150-2**. The specific location of the coupling structures **150-1**, **150-2** along the interface between each of the various sections **102**, **110**, **120** is not as important as determining the particular impedance to achieve the desired coupling.

FIG. **3** is a cross-sectional view of the antenna structure **100**. Here is more easily seen the cavity **130**, the couplings **150** and their relative orientation with respect to the center element **102** and ground plane elements **110**, **120**. The cavity **130** is seen to be disposed beneath a reference plane **147** provided by the vehicle skin. Lead lines **160** connect the respective feed points **106-1**, **106-3** (as well as the other two feed points, **106-2**, **106-4** not shown in FIG. **3**) to hybrid power combiners and/or transceiver circuitry. It is also seen here in more detail how the coupling structures **150-3** are connected between the upper surface of the element **110** and the sidewall **132** of the cavity **130**.

The nature of the antenna structure **100** including the center radiating cell **102** and surface impedance ground plane cells **110**, **120** is conformal to a plane with less than two inches of thickness. The nature of the structures is therefore to appear as a solid metallic surface using incorporated into the aircraft electro magnetic design time or other vehicles.

FIG. **4** illustrates an array **190** that includes four center cells **102-1**, **102-2**, **102-3**, **102-4** with interconnecting couplers **150**. An inner ground plane surface **110** and outer ground plane surface **120** surround all four cells **102** of the array **190**. Such arrays may include a fewer or greater number of center cells **102** and oriented in various square, rectangular, or other layouts. All cells **102** of the array **190** are placed over a single, common cavity **130**. The array **190** provides a conformal phased array that can exhibit various polarizations, depending upon how the individual cells **102** are driven at their feed points **106**. In one particular arrangement, the array can approximate the operation of a monopole antenna from a conformal, flat surface.

FIG. **5** is another implementation of a radiating cell **202**. This implementation still makes use of a cavity structure **230** but has radiating elements on each side of the cavity **230**. This form of radiating cell **202** thus consists of a total of eight triangular elements **203-1**, **203-2**, . . . **203-8** (only four of which are visible in FIG. **5**) with four triangular elements **203** located on each of the two faces of the rectangular cavity structure **230**. Eight terminal feeds **206-1**, **206-2**, . . . **206-8**, one for each triangular element, allow for interconnection to the other triangular elements to provide the desired polarization. In the illustrated embodiment, for each of the radiating faces, two terminals associated with two selected (i.e., vertical) triangular elements **203-2**, **203-4** are shorted together while the two terminals **206** associated with other two remaining horizontal triangular elements **203-1**, **203-3** are left open. This provides a desired vertical polarization and resulting omni-directional "monopole" pattern.

The walls of the cavity **230** are connected to their respective adjacent triangular elements by couplers **150**, which are preferably fixed-tuned to the desired wideband operation.

A vertical array of radiating unit cells **202** can also be realized. For example, three center cells **302-1**, **302-2**, **302-3** can be vertically stacked. This is shown in FIGS. **6**A and **6**B which are cross-sectional and front face views respectively of the same. Here the individual cells are connected to one another through meander lines.

A first cell **302** may provide coverage in a low frequency range of interest (such as from 30-88 MHz, and from 116-174 MHz), a second cell **302-2** may provide coverage in a medium bandwidth of interest (such as from 225-400 MHz), and a third radiating cell **302-3** provide coverage in an upper frequency band of interest (452-512 MHz).

FIG. **6**C is a more detailed view of a section A taken from FIG. **6**B. This shows the two adjacent cells **302-1**, **302-2** and respective meander lines **150** connecting them together. An optional conductive element **333** may be disposed between the meander lines **150**. The conductive element **333** may itself be electroactively controlled to give further precision to the coupling between cells **302-1**, **302-2**.

This single structure MultiBand Antenna solution (MBA) therefore consolidates three radiating unit cells **302** (sized respectively at 3 inches, 5 inches and 7 inches in height). Couplers **150** interconnect the stacked radiating units cells **302** to one another. This arrangement achieves low VSWR and broadband coverage. A single feed point can be connected to the bottom radiating unit cell **302-1** and diplexers provided (not shown) to further ensure isolation between the four frequency bands of interest.

An additional bowtie element **302-4**, as shown in FIG. **7**, with a separate feed can be positioned directly above the three vertically stacked elements **302-1**, **302-2**, **302-3**. The resulting array can be packaged in a blade-type enclosure suitable for attachment to high speed vehicles such as aircraft. The fourth element **302-4** can be 2.5 inch in height to cover the 2200-2500 MHz band.

The arrangement shown in FIG. **7** has an overall height of 17½ inches and is a solution that provides vertical polarization with an unidirectional pattern enabling −12.0 dBi of gain at 30 MHz, with monotonically increasing gain up to 512 MHz. A multichannel output can be provided by a diplexer embedded in the base **352** of the unit.

FIG. **8** shows one implementation of the frequency dependent coupling **150** as a meander line structure that provides passive control over impedance. This particular implementation is along the lines of that shown in U.S. Pat. No. 6,313,716. Elements of the meander line structure **150** are placed over an electrically conductive plate **505**. Alternating low impedance sections **520** run horizontally in a lower section of the structure, e.g., positioned most closely to the conductive plate **505**. High impedance horizontally running sections **510** are placed in an upper section of the structure, e.g., positioned further away from the conductive plate **505**. The low impedance sections **520** are electrically insulated from the conductive plate **505** such as by a Teflon insulator pad **530** located in close proximity to the plate **505**, to produce a relatively low characteristic impedance. Conversely, the high impedance sections **510** are characterized by a larger separation from the plate **505** to provide high characteristic impedance.

The low impedance sections **520** are connected by diagonal **550** or end **540** interconnects. The end interconnects **540** can be vertically (e.g., orthogonally) disposed metallic portions which connect the low impedance **520** and high impedance **510** sections to each other. Diagonal interconnects **550** can be used to connect a low impedance and high impedance section or to connect the high impedance section to a terminal (B). The serially interconnected alternating impedance sections provide mismatched switching along the underlying structure, which gives the meander line the desired "low-wave" propagation characteristics.

In this particular implementation of a conformed antenna in FIGS. **1-6**, ground plane cells **110**, **120** provide the conductive plate **505** and the terminal (B) is a cavity connection. As a result, the meander line **150** (in conjunction with the cavity walls) provides the desired low VSWR.

In another implementation, a Variable Impedance Transmission Line (VITL) can provide the desired passively tunable coupling **150**. FIG. **9** is one such implementation that provides this behavior. This approach enables inductive tuning of the conformal antenna structure **100** (FIG. **1**) with a reduced aperture size as compared to what would otherwise be necessary to achieve a given efficiency.

More particularly, the VITL implementation **150**, shown in FIG. **9**, is composed of serially interconnected, alternating low impedance and high impedance transmission line sections. As shown, this can be formed by a meander line embedded as a "back-and-forth" metallic strip **610** in or on an interposed dielectric substrate **620**. The high impedance sections decrease in size along the metallic strip. This arrangement thus provides mismatched switch impedance along the structure, and results in the desired "slow wave" propagation characteristic.

FIG. **10** shows another embodiment of a VITL making use of electroactively tuned actuator sections. As with FIG. **9**, the implementation shown in FIG. **10** is a side view with the layer thicknesses exaggerated. In this implementation, called a Tunable Variable Impedance Transmission Line (TVITL), electroactive actuators **720** are disposed between the metal transmission line sections **710** and the dielectric **730**. Upon application of an electric field to the actuators **720**, they will change in thickness, and thereby alter the effective spacing between the dielectric layers **730** and metal **710** layers. Meta-ferrite properties are therefore observed without using any actual ferrite material.

Control voltages can be applied to the electroactive actuators according to the techniques described in co-pending U.S. patent application Ser. No. 13/431,217 filed Mar. 27, 2012 entitled "Tunable Transversal Structures", the entire contents of which are hereby incorporated by reference.

While this invention has been particularly shown and described with references to example embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope of the invention encompassed by the appended claims.

What is claimed is:

1. An apparatus comprising:

a cavity having conductive walls disposed below a reference plane;

a center radiating surface located on or above the reference plane and located above the cavity;

one or more surrounding ground plane surfaces, disposed on and co-planar with the reference plane above the cavity, and outboard of the center radiating surface, the ground plane surfaces electrically surrounding the center radiating surface; and

frequency dependent couplings, disposed between the center radiating surface and at least one of the surrounding ground plane surfaces, and also disposed between at least one of the surrounding ground plane surfaces and at least one conductive wall of the cavity;

and further wherein

the center radiating surface comprises a quadrilateral surface having four sides;

the quadrilateral surface area comprises four conductive triangular shaped surfaces, disposed such that bases of the triangular surfaces are aligned with respective sides of the quadrilateral surface; and

the surrounding ground plane surfaces further comprise:

a set of four ground plane surfaces, each disposed adjacent to and outboard of a respective one of the four sides of the quadrilateral surface; and

at least four frequency dependent couplings, each frequency dependent coupling disposed between a respective one of the ground plane surfaces and quadrilateral surfaces.

2. The apparatus of claim **1** wherein the center radiating surface further comprises:

an array of two or more center radiating surfaces, with the array disposed inboard of the surrounding ground plane surfaces.

3. The apparatus of claim **1** where the conductive triangular surfaces each have a respective feed point, with the feed points from two opposing triangular surface shorted together, and the other two remaining feed points being left open.

4. The apparatus of claim **1** further comprising:

a second center radiating surface disposed on or above a second reference plane on an opposite side of the cavity from the first reference plane;

one or more second surrounding ground plane surfaces, disposed on and coplanar with the second reference plane and outboard of the second center radiating surface, the second ground plane surfaces electrically surrounding the second center radiating surface;

a second set of frequency dependent couplings, disposed between the second center radiating surface and at least one of the surrounding second ground plane surfaces, and also disposed between at least one of the surrounding second ground plane surfaces and at least one conductive wall of the cavity.

5. The apparatus of claim **4** providing an approximate monopole response pattern.

6. The apparatus of claim **1** wherein the frequency dependent couplings are meander lines.

7. The apparatus of claim **1** wherein the frequency dependent couplings are Variable Impedance Transmission Lines (VITLs).

8. The apparatus of claim **7** wherein the frequency dependent couplings are further implemented with two or more transmission line sections disposed in parallel with one another, and a dielectric section disposed between at least two of the transmission line sections.

9. The apparatus of claim **8** wherein the frequency dependent couplings further comprise:

an electroactive layer, disposed between the transmission line sections and the dielectric section.

10. The apparatus of claim **1** wherein the surrounding ground plane surfaces further comprise:

a set of outer plane surfaces, each disposed coplanar with and adjacent to and outboard of a respective one of the set of four ground plane surfaces; and

additional frequency dependent couplings disposed between each of the set of outer surfaces and each of the set of ground plane surfaces.

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UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 9,147,936 B1
APPLICATION NO. : 13/536445
DATED : September 29, 2015
INVENTOR(S) : John T. Apostolos

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the Claims:

Claim 3, Col. 8, line 1 should read:
3. The apparatus of claim **1** wherein the conductive triangular

Claim 3, Col. 8, line 3 should read:
points from two opposing triangular surfaces shorted together,

Claim 3, Col. 8, line 4 should read:
and the feed points being left open.

Signed and Sealed this
Eighth Day of March, 2016

Michelle K. Lee

Michelle K. Lee
Director of the United States Patent and Trademark Office